

## GASP III. JO36: A CASE OF MULTIPLE ENVIRONMENTAL EFFECTS AT PLAY?

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## ABSTRACT

The so-called jellyfish galaxies are objects exhibiting disturbed morphology, mostly in the form of tails of gas stripped from the main body of the galaxy. Several works have strongly suggested ram pressure stripping to be the mechanism driving this phenomenon. Here, we focus on one of these objects, drawn from a sample of optically selected jellyfish galaxies, and use it to validate SINOPSIS, the spectral fitting code that will be used for the analysis of the GASP (GAs Stripping Phenomena in galaxies with MUSE) survey, and study the spatial distribution and physical properties of gas and stellar populations in this galaxy. We compare the model spectra to those obtained with GANDALF, a code with similar features widely used to interpret the kinematic of stars and gas in galaxies from IFU data. We find that SINOPSIS can reproduce the pixel-by-pixel spectra of this galaxy at least as good as GANDALF does, providing reliable estimates of the underlying stellar absorption to properly correct the nebular gas emission. Using these results, we find strong evidences of a double effect of ram pressure exerted by the intracluster medium onto the gas of the galaxy. A moderate burst of star formation, dating between 20 and 500 Myr ago and involving the outer parts of the galaxy more strongly than the inner regions, was likely induced by a first interaction of the galaxy with the intracluster medium. Stripping by ram pressure, plus probable gas depletion due to star formation, contributed to create a truncated ionized gas disk. The presence of an extended stellar tail on only one side of the disk, points instead to another kind of process, likely a gravitational interaction by a fly-by or a close encounter with another galaxy in the cluster.

*Keywords:* galaxies:general — galaxies: evolution — galaxies: kinematics and dynamics — galaxies: clusters: individual (Abell 160) — galaxies: ISM

## 1. INTRODUCTION

The evolution of galaxies is driven by physical mechanisms of either internal or external nature. Among the first ones are the processes related to stellar evolution (e.g. the star formation activity, supernovae explosions, etc.), nuclear activity (accretion on a supermassive black hole and the related release of mechanical energy), and to the whole structural configuration of the different components (e.g. angular momentum reconfiguration by stellar bars). As for the external ones, interactions with galaxies, with the gravitational potential of large, massive structures (such as galaxy groups or clusters), and with the dense, hot gas of the intracluster medium, are among those playing the major role.

Several of such environment-dependent processes have been identified and proposed to explain the different evolutive paths that galaxies in clusters follow with respect to isolated ones, both regarding their stellar content (or, equivalently, their star formation history) and to their morphology. These include harassment (repeated high velocity encounters with galaxies in the cluster, [Moore et al. 1996](#)), starvation/strangulation (the removal, during the cluster collapse, of the galactic gas halo which fuels the star formation, [Larson, Tinsley, & Caldwell 1980](#); [Balogh, Navarro, & Morris 2000](#)), ram pressure stripping (the removal of the interstellar gas by means of high velocity interactions with the intracluster medium, e.g. [Gunn & Gott 1972](#); [Faltenbacher & Diemand 2006](#), [Takeda, Nulsen, & Fabian 1984](#)), thermal

evaporation (Cowie & Songaila 1977), major and/or minor mergers (e.g. Toomre 1977; Tinsley & Larson 1979; Mihos & Hernquist 1994; Springel 2000), or tidal effects of the cluster as a whole (e.g. Byrd & Valtonen 1990; Valluri 1993).

As the star formation history of a galaxy crucially depends on the amount of gas available, processes removing, adding, or even perturbing the gas, are ultimately determining the evolution and the fate of a galaxy, at least as far as the stellar content is concerned.

Evidences of abruptly interrupted star formation due to gas removal (e.g. Steinhäuser, Schindler, & Springel 2016) as well as of enhancement of star formation (Boselli & Gavazzi 2006) are found in the cluster galaxy population. The latter phenomenon in particular, is believed to be caused by the early effect of ram pressure of the hot intracluster medium that compresses the gas of the galaxy providing the dynamical instabilities needed to kick-start a star formation event.

Spectacular examples of distorted morphologies due to gas losses, are the so-called jellyfish galaxies. Firstly dubbed as such by Smith et al. (2010) to describe the appearance of filaments and knots departing from the main body of the galaxy, these objects are mostly found in clusters both locally (see, e.g. Fumagalli et al. 2014; Merluzzi et al. 2016; Abramson et al. 2016) and at high redshift (e.g. Cortese et al. 2007; Ebeling, Stephenson, & Edge 2014; McPartland et al. 2016). The availability of new generation Integral Field Units (IFU) such as the Multi Unit Spectroscopic Explorer (MUSE) on 8m class telescopes, has opened a new window to study the physical processes at play in these galaxies.

GASP (GAs Stripping Phenomena in galaxies with MUSE) is an ESO large program (P.I. B. Poggianti) which uses the second generation IFU MUSE mounted on the Nasmyth focus of the UT4 at the VLT, to observe a sample of 124 low redshift ( $z = 0.04 - 0.07$ ) galaxies with evidence of disturbed morphology in optical images of clusters from WINGS/OMEGAWINGS project (Fasano et al. 2006; Gullieuszik et al. 2015). GASP was granted 120 hours of time spread over four semesters from Period 96 (October 2015), and the second half of the observational campaign is currently being performed.

The ultimate goal of this project is to take a step forward in the understanding of the processes that remove gas in galaxies halting, in this way, the ongoing star formation processes. To which extent is the environment playing a role in gas stripping? Where is this more efficient? Why is it occurring and by which mechanism(s)? These are the most urgent questions this project tries to address. We refer the reader to Poggianti et al. (2017) for a more detailed presentation of the survey, its characteristics, and its goals.

In this work we focus on JO36, a galaxy drawn from the GASP sample. In the first part of the paper, we use it as a test case to validate SINOPSIS, the spectrophotometric fitting code developed for the spectral analysis of the whole survey. To this aim, we perform a detailed comparison between SINOPSIS and GANDALF (Sarzi et al. 2006), a similar code that has been widely used to interpret the kinematic of stars and gas in galaxies from IFU data.

In the second part of the paper, we use the outputs of SINOPSIS to characterise the properties and distribution of the stellar populations in the galaxy, and give an interpretation of its observed characteristics in relation to its position and dynamical status within the cluster it belongs to. Exploiting archival data, we calculate the dust mass and use this to derive an estimate of the total gas mass, while X-ray observations are used to constrain the possible presence of an active galactic nucleus (AGN).

Like all the papers of the GASP series, we will assume a standard  $\Lambda$ CDM cosmology, with  $H_0 = 70$ ,  $\Omega_M = 0.3$ , and  $\Omega_\Lambda = 0.7$ . Similarly, stellar masses and star formation rates are calculated assuming a Chabrier (2003) Initial Mass Function (IMF). An observed redshift of 0.04077 like that of the galaxy under investigation, in this cosmology, corresponds to a luminosity distance of 180.0 Mpc and to an angular scale of  $0.81''/\text{kpc}$ , which results in a physical spaxel size of about 160 pc/spaxel for MUSE.

## 2. DATA

As already outlined in the Introduction, this work provides a detailed analysis of a single galaxy drawn from the GASP sample. JO36 was selected from the sample of jellyfish candidates of Poggianti et al. (2016) found in the OmegaWINGS database (Gullieuszik et al. 2015). Also known as 2MFGC00903, or WINGSJ011259.41+153529.5, this galaxy was chosen for testing and validating SINOPSIS because dominated by the emission of the stellar populations as opposed to the nebular one.

JO36 (RA=01h12m59.4s; DEC=+15d35m29s) is a disturbed galaxy with an assigned stripping class value JClass=3 (on a 1 to 5 scale, where 5 represents the maximum morphological disturbance in the optical, see Poggianti et al. 2016) belonging to the Abell cluster A160. The galaxy is classified as a Sc spiral seen almost edge-on, has a V band magnitude of 15.5, is found at a projected radial distance of about 422 kpc from the Brightest Cluster Galaxy (BCG), and was recognised in optical images because of the presence of a bright optical tail, both in the V and B band, departing from the galaxy disk towards the south. MUSE data for this object were taken in October 10th, 2015, with an exposure of 2700

s.

The data reduction for the whole GASP project is described in the survey’s presentation paper, [Poggianti et al. \(2017\)](#), and we refer the reader to this work for all the details about this.

### 3. THE SPECTRAL FITTING CODE

In this section we summarise the main features of SINOPSIS, and compare its performances and results to those obtained by analysing the very same dataset with GANDALF, by [Sarzi et al. \(2006\)](#), a code which is commonly used to perform similar analysis on IFU data (see, e.g. [Bacon et al. 2001](#); [de Zeeuw et al. 2002](#), and other papers of the SAURON survey).

The choice of a comparison with GANDALF among many other similar codes, is dictated by the need of subtracting, for a major part of the analysis of galaxies in GASP, the stellar component from the nebular lines when performing spatially resolved analysis on the gas properties. GANDALF is one of the most used tools to perform such subtraction, and was hence chosen as a reference.

#### 3.1. Modeling details

SINOPSIS<sup>1</sup> (SIMulatiNg OPTical Spectra wIth Stellar population models), is a spectrophotometric fitting code that reproduces the main features of galaxy spectra in the ultra-violet to near-infrared spectral range. While we refer the reader to former papers describing in more detail the code’s approach, its main characteristics, and the reliability of the results it provides ([Fritz et al. 2007, 2011](#)), here we summarise its most important facts.

The reader who is not interested in the technical details can safely skip this Section and go directly to Sect. 4.

SINOPSIS has its roots on the spectral fitting code used by [Poggianti, Bressan, & Franceschini \(2001\)](#) to reproduce the stacked optical spectra of a sample of Luminous Infrared Galaxies of different spectral types, and it has since then been applied to derive the physical properties (stellar mass, dust attenuation, star formation history, mean stellar ages, etc.) of galaxies in various samples ([Dressler et al. 2009](#); [Fritz et al. 2011](#); [Vulcani et al. 2015](#); [Guglielmo et al. 2015](#); [Paccagnella et al. 2016](#); [Cheung et al. 2016](#)). It has been validated with a detailed comparison with both simulated spectra of galaxies ([Fritz et al. 2007](#)) and other datasets and models ([Fritz et al. 2011](#)), and it has been so far used to fit several thousands of optical spectra.

<sup>1</sup> SINOPSIS is publicly available under the MIT open source licence, and can be downloaded from <http://www.crya.unam.mx/gente/j.fritz/JFhp/SINOPSIS.html>.

#	$\lambda_{inf}$	$\lambda_{sup}$
1	4600	4750
2	4845	4853
3	4858	4864
4	4870	4878
5	5040	5140
6	5210	5310
7	5400	5500
8	5650	5800
9	5955	6055
10	6150	6250
11	6400	6490
12	6620	6690
13	6820	6920
14	7110	7210

**Table 1.** List of photometric windows, defined by the respective lower and upper wavelength, where the continuum flux is calculated to compare observed and model spectrum.

A number of other codes can be found in the literature to serve similar purposes, and to derive the properties of the stellar populations and extinction in galaxies from their optical spectra, including e.g. STARLIGHT ([Cid Fernandes et al. 2005](#)), STECKMAP ([Ocvirk et al. 2006](#)), VESPA ([Tojeiro et al. 2007](#)), GOSSIP ([Franzetti et al. 2008](#)), ULySS ([Koleva et al. 2009](#)), POPSYNTH ([MacArthur, González, & Courteau 2009](#)), FIREFLY ([Wilkinson et al. 2015](#)), FIT3D ([Sánchez et al. 2016](#)) (but this list is most likely not complete). SINOPSIS shares similar features to some of these, but carries some substantial improvements, with respect to these codes, as well.

In order to reproduce an observed spectrum, the code calculates the average value of the observed flux in a pre-defined set of spectral bands (see Table 1), accurately chosen for the lack of prominent spectral features such as emission and absorption lines, and the equivalent width values of significant lines (i.e. the hydrogen lines of the Balmer series plus the [OII] 3727 Å line), both in emission and in absorption. It then compares them to the same features in a theoretical model which is created as follows. From a set of  $\sim 200$  mono-metallicities SSP spectra with ages spanning the range between  $10^4$  and  $14 \times 10^9$  years, SINOPSIS creates a new set, with a reduced number of model spectra, by binning the models of the original grid with respect to the SSP’s age. In this way, the number of theoretical spectra shrinks to only 12, for any given metallicity value. The choice of the age bins is made based on presence and intensity of spectral features as a function of age (see [Fritz et al. 2007](#), for more details).

To produce a model spectrum, each of the 12 age–

binned spectra is multiplied by a given stellar mass value, and the effect of extinction is applied to each one of them before they are added together to yield the final model. One of the distinctive features of SINOPSIS is that it is possible to allow for differential extinction as a function of the stellar age. In this way, the code simulates a selective extinction effect (Calzetti, Kinney, & Storchi-Bergmann 1994), where the light emitted by the youngest stellar populations is most likely to be affected by the presence of the dust that is typically abundant in star forming molecular complexes. Once a stellar population ages, it progressively gets rid of this interstellar medium envelop, either by means of supernova explosions, which will blow it away, or because of the proper motions of the star clusters, or by a combination of the two effects.

Dust is found in the interstellar medium and is well mixed with the stars. A proper treatment of its extinction effect on the starlight would require the use of radiative transfer models, which can fully take into account the 3-D geometry of dust and stars, and their relative distribution (see, e.g., the review by Steinacker, Baes, & Gordon 2013). This is prohibitive for two reasons: one is the computational effort required to calculate such kind of models, and the second is the lack of a detailed enough knowledge of the spatial distribution of these two components in any given galaxy.

Just like many other spectral fitting codes, SINOPSIS includes the effect of dust extinction by modelling it as a uniform dust layer in front of the source. While this is indeed a simplification, Liu et al. (2013) have demonstrated that adopting a slab, foreground dust screen, is a fair representation of the effects dust has on starlights at large scales. Furthermore, the mix of stellar ages and extinction can be naturally taken into account by the age-dependent way of treating dust attenuation that SINOPSIS allows.

Different extinction and attenuation laws can be chosen including, among others, the attenuation law from Calzetti, Kinney, & Storchi-Bergmann (1994), the average Milky way extinction curve (Cardelli, Clayton, & Mathis 1989), or the Small and Large Magellanic Clouds curves (Fitzpatrick 1986).

Another key feature of SINOPSIS is the use of SSP models for which we have calculated the effect of nebular gas emission. To our knowledge, SINOPSIS is currently the only spectral fitting code that includes SSP models with emission lines. This is a great advantage for a number of reasons: emission lines in the observed spectra need not to be masked for the fitting, a reliable value for dust extinction can be calculated (even when  $H\beta$  is not observed), and star formation rate can be automatically estimated as well. Last but not least, especially for the purposes of the GASP project, correction of the under-

lying absorption in Balmer lines is performed in a self-consistent way, by simultaneously taking into account both the absorption and emission components.

The calculation of the lines' intensities is obtained by pre-processing the SSPs spectra energy distribution (SED) with ages  $\leq 5 \times 10^7$  years through the photoionisation code CLOUDY (Ferland 1993; Ferland et al. 1998, 2013). The adopted parameters are those typical of a HII region (see also Charlot & Longhetti 2001): hydrogen average density of  $10^2$  atoms  $\text{cm}^{-1}$ , a gas cloud with a inner radius of  $10^{-2}$  pc, and a metal abundance corresponding to the metallicity of the relative SSP.

The lines for which the luminosities are calculated include hydrogen of the Balmer (from  $H\alpha$  to  $H\epsilon$ ), Paschen (from  $Pa\alpha$  to  $Pa\delta$ ), Brackett (from  $Br\alpha$  to  $Br\delta$ ), and Lyman ( $Ly\alpha$  and  $Ly\beta$ ) series. Luminosity of UV and optical forbidden lines from various other elements (such as [OI], [OII], and [OIII], [NII], [SII] and [SIII]) are calculated as well.

As a sanity check, we have calculated the luminosity of the  $H\alpha$  line corresponding to a constant star formation rate over  $10^7$  years, and checked that this value is consistent with the factor typically used to convert an  $H\alpha$  luminosity into a star formation rate value. We found a good agreement, when considering a Chabrier (2003) IMF (see Kennicutt & Evans 2012, for a recalibration of this SFR indicator), as it is the case for the SSPs version (discussed below) currently implemented in SINOPSIS.

In order for SINOPSIS to properly deal with IFU datacubes, a number of changes and improvements were made with respect to the versions presented in Fritz et al. (2007) and Fritz et al. (2011). These are very briefly described hereafter:

- SINOPSIS can now ingest observed spectra in fits format. Data format can be either 1D (a single spectrum), 2D (a series of spectra, as e.g. provided by multi-slit or fibre fed spectrographs), or 3D (for e.g. IFU such as MUSE);
- most of the results are now saved on datacubes in fits format, with each plane containing one of the properties typically derived from this kind of analysis (e.g. pixel-by-pixel stellar mass, extinction, star formation rate, stellar age, etc. See Fritz et al. 2011 for a detailed description of the meaning of each parameter);
- a new set of SSP models by Charlot & Bruzual (2017) is used, which has higher spectral and age resolution, and a larger number of metallicity values (namely 13, from  $Z=0.0001$  to  $Z=0.04$ , as compared to the 3 default values used before). This new models dataset includes the most recent version of the PADOVA evolutionary tracks from



Bressan et al. (2012) (PARSEC), and have been coupled with stellar atmosphere libraries from several sources depending on the wavelength coverage, on the luminosity, and on the effective temperature (see Gutkin, Charlot, & Bruzual 2016, for the full compilation of the adopted stellar spectra). The evolutionary tracks include the treatment of the Wolf-Rayet phase, for stars typically more massive than  $25 M_{\odot}$ . The assumed IMF is Chabrier (2003) with masses in the range 0.1 to  $100 M_{\odot}$ ;

- one of the outputs includes now the purely stellar emission, that is of the model spectrum without the nebular emission lines component. These are calculated from the best fit parameters but using instead the SSP set with pure stellar emission;
- when spectra from different regions of a galaxies are considered, it is possible that the velocities of the gas and those of stars are different. For our purposes, this means that during the spectral fitting, when using redshifts calculated from absorption lines (i.e. that of the stellar component), the center of lines in emission could be displaced with respect to the absorption component. This might turn into a miscalculation of the line's equivalent width, or sometimes even to a non-detection. To overcome this possible issue, we now allow the simultaneous use of redshifts calculated from the two components. If no emission lines are detected, only the stellar redshift is used, while if emission lines are present, the measurement of the equivalent width is performed using the emission-line redshift for lines in emission;
- SINOPSIS has been optimised from the computational efficiency point of view, and can successfully reproduce one optical spectrum in less than 1 second on a 3.5 GHz Intel Core i7 machine (running Mac OS X Version 10.10.5). The code is currently not parallelised and can only use one core at the time. We are planning to implement multithreading to exploit the full resource power of multi-core computers for the analysis of multiple spectra/IFU data, which has proven to be quite computational demanding.

### 3.2. Comparison with GANDALF

As already outlined in Sect. 3.1, SINOPSIS has been used to analyze spectra from different instruments and various surveys. Still, an application to integral field data was so far missing. Even though, in principle, it all comes down to correctly reproduce the most significant features of an optical spectrum, we have performed

a number of tests to check the reliability of the results, by comparing our outcomes with those obtained with GANDALF (Sarzi et al. 2006), an IDL tool which shares similar features with SINOPSIS, but that focuses mostly on the analysis and interpretation of the emission and absorption lines' characteristics to derive the stellar and gas kinematics, even though the stellar population properties can be inferred as well.

Both codes attempt to reproduce, by means of theoretical spectra, the observed features of an optical spectrum. The underlying models are very similar, as they both use stellar atmosphere from MILES (Vazdekis et al. 2010 for GANDALF and the similar version of Sánchez-Blázquez et al. 2006 for SINOPSIS), at a spectral resolution of  $\sim 2.5 \text{ \AA}$ . They both provide an emission lines-free model spectrum.

The main differences between the two codes can be summarised as follows:

- the models used by SINOPSIS already include the nebular emission, which has been self-consistently calculated using the SSP spectra as an input source fed into the photoionisation code CLOUDY. GANDALF, instead, reproduces them as gaussian functions, fitting not only their intensity, but their width and central wavelengths as well;
- SINOPSIS assumes a physical extinction curve (either from models or derived from observations) to account for dust reddening in the models before matching to the observed ones, while GANDALF corrects for the effect of dust by multiplying the model spectra by  $n_{th}$ -order Legendre polynomials;
- SINOPSIS reconstructs the characteristics of the stellar populations even when the S/N is not optimal, while GANDALF has been mostly used to interpret high signal-to-noise (S/N) spectra.

We have run the two fitting tools on a region of JO36, specifically on a rectangle of  $109 \times 255$  spaxels which fully includes all of the galaxy's disk, and limited the wavelength range to the spectral window between 4750 and  $\sim 7650 \text{ \AA}$ , hence not taking into account the reddest part of the spectrum, much less rich in features that are crucial for the purposes of the study we intend to carry on.

We have analyzed the performances of the two codes by calculating, a posteriori, the goodness of the fit to the continuum emission, hence not taking into account any spectral line (a further check is done on the equivalent width values of the  $H\alpha$  and  $H\beta$  lines, in a separate comparison). To do so, we have defined 14 spectral windows with a width of  $\sim 100 \text{ \AA}$ , except for a few cases where the width was shorter than this value, due to the

necessity of sampling a specific continuum emission region, while at the same time avoiding nearby emission or absorption features. These were chosen in order to homogeneously sample the whole spectral range (see Table 1 for the details).

For both codes, we have calculated a goodness index,  $\Gamma$ , for each of the aforementioned bands, defined as:

$$\Gamma = \sum_{j=1}^N \Gamma^j = \sum_{j=1}^N \left( \frac{F_o^j - F_m^j}{\sigma^j} \right)^2. \quad (1)$$

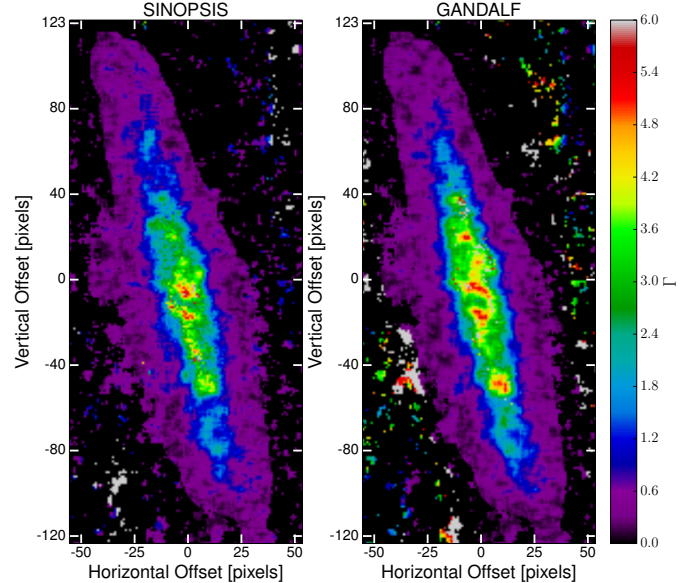
where  $F_o^j$  and  $F_m^j$  are the average fluxes calculated over the  $j$ -th band, of the observed and model spectrum, respectively.  $\sigma^j$  is the uncertainty on the observed flux in that band, calculated as the standard deviation of the flux. Hence,  $\Gamma_i$  is the goodness index relative to a specific band. Note that, with the definition of the flux errorbars we have chosen, we might be slightly overestimating the uncertainties on the flux in the highest S/N spectra. This is, however, irrelevant for the relative comparison as the errors are the same when the  $\Gamma$  index is calculated for SINOPSIS and GANDALF. In principle, one would expect that values of  $\Gamma^j$  lower than 1 (that is, with the model flux being within  $1\sigma$  from the observed one), are to be considered acceptable fits. In reality, the values are always much smaller in the vast majority of the cases.

We have constructed maps of both the  $\Gamma$  and  $\Gamma^j$  values for each of the 14 bands, so that we could check for the presence of systematic differences in any of the spectral ranges defined above.

The value of the goodness index, averaged over all the spaxels, was found to be 0.85 and 1.37 in the case of SINOPSIS and of GANDALF, respectively, indicating that the two codes provide, globally and on average, very satisfying fits to the observed data, with SINOPSIS performing slightly better with respect to GANDALF.

We note that, in order for SINOPSIS to provide satisfactory fits, in particular towards the center of the galaxy, we needed to relax the constraints on the maximum values of dust extinction, in particular those of the oldest stellar populations. This parameter is, in SINOPSIS, left free to vary as a function of the stellar age, as it is expected that the light from the youngest stars is more affected by the presence of dust. Normally, the upper limits of the values that dust extinction can reach for each stellar population are an inverse function of their age. This can be viewed on an equal footing with a prior which helps limiting the effect of possible degeneracies.

Allowing older stars to be more heavily affected by dust extinction, is not a mere matter of increasing the degree of freedom of the parameters, but has an actual physical meaning: the bulge of the galaxy is the most crowded area, and the light emitted by old stars is easily



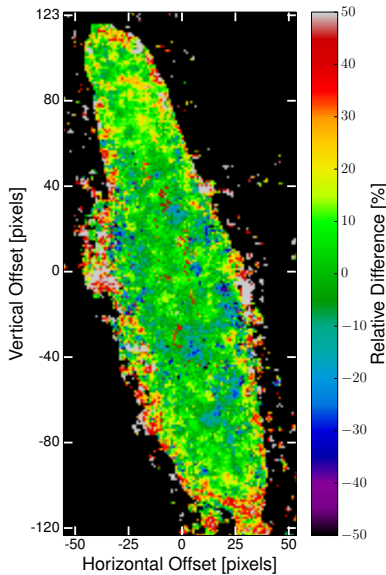
**Figure 1.** Maps of the goodness index (see Eqn. 1) for SINOPSIS (left-hand panel) and GANDALF (right-hand panel), for the central parts of the JO36. The values are displayed in linear scale with values running from 0 to 6.

contaminated both by other stellar populations with a whole range of stellar ages, but also by the presence of dust, located anywhere along the line of sight. The orientation of the galaxy is, in fact, very far from being face on, a configuration which would minimise the dust reddening effect (see, e.g. De Looze et al. 2014), and light coming from the innermost part gets contribution both from the bulge and from the disk, which is likely to contain the majority of the dust.

In Fig. 1 we show the  $\Gamma$  map calculated as explained above for both codes (note that the values for each spaxel are calculated according to Eqn. 1, hence not normalised to the total number of observables). A visual comparison of the two maps in Fig. 1, confirms the aforementioned result, highlighting that SINOPSIS performs slightly better with respect to GANDALF, at least as far as the continuum emission is concerned.

It can be easily noted that the  $\Gamma$  values decrease, on average, as a function of the galactocentric distance for both models. This is due to the fact that the spectra become fainter as we approach the galaxy's outskirts, and the S/N hence gets lower. This increases the observed uncertainties on the fluxes, and it consequently makes the fits more degenerate giving, as a result, lower values of the goodness index.

As for the other observed features, namely the spectral lines, an automatic comparison with the data is much less straightforward, due to the complications of properly measure emission and absorption lines, especially



**Figure 2.** Map of the relative difference in the  $H\beta$  equivalent width values of the two models, calculated as in Eqn. 2, for each spaxel.

in the lowest S/N spectra. Hence, we have performed two quality checks: in the first one, we have compared observed and model spectra, while in the second we focussed on possible differences between the models provided by the two codes.

For the first one, we have visually inspected the fits provided by the two codes to the observed spectra, around the  $H\alpha$  and  $H\beta$  lines, checking for differences. This was done in a randomly chosen sample of spaxles (approximately 150 spectra of various S/N were visually inspected). No significant differences were found between the two models. On a minor fraction of the spectra in this control sample (less than 10%), SINOPSIS better recovers the  $H\beta$  emission, especially when deeply embedded within the absorption profile.

In the second check, we have calculated the equivalent widths of the  $H\alpha$  and of the  $H\beta$  lines from the best fits, and compared the values from the two models. On average, we found a difference of about 15% in the value of the equivalent width of the two lines when comparing measurements in each spaxel. In Fig. 2 we show the map of the spaxel-by-spaxel differences, expressed in percentage of the  $H\beta$  equivalent width value (which is the feature displaying the largest difference), calculated as:

$$\Delta_{\beta} = \frac{EW_s - EW_g}{EW_s} \quad (2)$$

where  $EW_s$  and  $EW_g$  are the equivalent width values, expressed in  $\text{\AA}$ , of the SINOPSIS and GANDALF models, respectively.

As it is displayed in Fig. 2, the differences are mostly within a  $\sim 5\%$  across all the galaxy, with very few exceptions where the discrepancy can be as high as  $\sim 50\%$ , but mostly in the outskirts of the disk, where the S/N is lower. We have visually inspected the fits from both codes for a sample of these spaxels with the highest discrepancies and found that, in the vast majority of cases, it is GANDALF which is displaying issues fitting the observed line (e.g. because of a poor fit of the continuum emission near the line, which hence affects the line's measurement itself).

We conclude that the two codes perform, with respect to the determination of the spectral continuum emission and of the hydrogen absorption lines intensity, in a very similar way. This gives us strong confidence in the models provided by SINOPSIS in particular with respect to the correction of the absorption component in Balmer lines, that was our major interest.

#### 4. RESULTS

We now present the results of the kinematic and stellar populations analysis. The stellar and gas velocities were derived by means of external packages. In particular, the fitting and characterisation of the emission lines has been performed by exploiting the KUBEVIZ (Fossati et al. 2016) code, while the stellar velocities were measured by the pPXF software (Cappellari & Emsellem 2004; Cappellari 2012), which works in Voronoi binned regions of given S/N (10 in this case; see Cappellari & Copin 2012).

The stellar populations properties were obtained by applying SINOPSIS to the observed datacube in each spaxel with a reliable redshift determination, using three sets of SSP spectra with fixed metallicity values (namely,  $Z = 0.004$ ,  $Z = 0.02$ , and  $Z = 0.04$ ). Whenever a stellar redshift was available, this was used for the spectral fitting, while the equivalent widths of emission lines were measured using the redshift value derived from emission lines. About 15000 observed spectra were analyzed (the runtime takes approximately 8 hours).

##### 4.1. The stellar and gas kinematic

The stellar kinematic was derived, as customary for this kind of data, from the analysis of the characteristics of absorption lines, while the kinematical properties of the gas were inferred from a similar analysis of the  $H\alpha$  emission line, using the aforementioned tools. In Fig. 3 we show the velocity map of the stellar and gas components, while Fig. 4 presents the radial velocity profiles along the major axis for stars (red triangles) and gas (blue, dashed line). Differences between the velocities of the two components are shown as green diamonds on the lower panel. At radii larger than  $\sim 10$  kpc the trend becomes much noisier due to the fewer usable spaxels

and to the more uncertain velocity determination. A cut to a  $S/N=4$  has been applied in the gas velocity map.

While following the same pattern in the velocity profiles, the gas has higher velocities throughout almost the whole disk with respect to the stars. This is in agreement with the expectation that the asymmetric drift of the stars (with  $\sigma \sim 140$  km/sec in the bulge) is significantly larger than that of the ionized gas (see e.g. [Martinsson et al. 2013](#)).

The radial distribution of the stellar velocities displays a monotonic gradient out to radii of about 10 kpc, with values as high as  $\sim 200$  km/s, as expected from a nearly edge-on galaxy, and is a clear indication of a rotationally supported disk. After this radius, the velocity gradient flattens out in the north part of the disk while displaying a slight bump on the south side, reaching higher velocities further out. These velocities correspond to stars observed in a tail extending by about 5 kpc southwards, where the (stellar) radial velocities are the highest found in the disk, with (negative) values of about 270 km/s.

The “rotational axis” of the gas component (i.e. the locus of close-to-zero velocities) visible in Fig. 3 as a green strip, is bent in a twisted “U” shape, with 0-velocity gas found in the outer disk, as far as  $\sim 5$  kpc away from the minor axis. Such feature is similar to that observed by [Merluzzi et al. \(2016\)](#) in the jellyfish galaxy *SOS90630* of the Shapley supercluster.

Using an ad hoc N-body/hydrodynamical simulation, they found that the gas velocity field, and this very feature in particular, can be successfully reproduced when RPS is acting on an almost edge-on geometrical configuration (see their Fig. 18 and 27), with the galaxy moving in the opposite direction with respect to the concavity.

A careful inspection of the gas velocity map, highlights asymmetries in their values, with negative velocities extending well beyond the galaxy’s center towards the north, out to a distance of about 8 kpc in the eastern side of the disk (see the region marked with “F” in Fig. 3). Similarly, on the same side but towards the south, there is a clear inversion in the gas velocities, going from negative to positive values (region “E” on the same Figure).

Four  $H\alpha$  blobs are visible towards the south, detected with  $S/N$  from  $\sim 10$  (the regions labelled as “B”, “C”, and “D”) to more than 50 (region “A”, the southernmost one). The most luminous one, region A, is clearly detected on the V band image of WINGS and OmegaWINGS data as well. The velocities of blobs A, B, and C, are quite compatible with those observed in the southern disk, while those in region D are similar to those of the northern side. A feature with similar velocities is found on the south-east side of the disk (labelled as “E” in Fig. 3), with counter rotating velocities with respect

to the gas on this side of the galaxy.

The map of the stellar velocities shows a clear evidence of a tail extending about 5 kpc from the southern disk, with velocities up to about 270 km/s, following the pattern observed in the inner disk, while the northern side shows no evidence of a similar structure, which is absent from WINGS images as well.

#### 4.2. The spatially resolved gas properties

We have created diagnostic diagrams (see, e.g. [Kewley et al. 2006](#)) using emission lines lying within the observed range of our data (i.e.  $H\beta$  [OIII] 5007 Å, [OI] 6300 Å,  $H\alpha$ , [NII] 6583 Å, and [SII] 6716+6731 Å) to derive the characteristics of the ionising sources as a function of the position, and detect the possible presence of an AGN. The lines’ intensities were measured after subtraction of the continuum, exploiting the pure stellar emission best fit model provided by SINOPSIS, so to take into account any possible contamination from stellar photospheric absorption.

The three diagrams we have used, namely  $\log[NII]/H\alpha$  vs  $\log[OIII]/H\beta$  (shown in Fig. 5),  $\log[OI]/H\alpha$  vs  $\log[OIII]/H\beta$ , and  $\log[SII]/H\alpha$  vs  $\log[OIII]/H\beta$  (not presented in this paper), are concordant in excluding the presence of an AGN. We consider this result to be quite robust, given that in the center of the galaxy, where a possible AGN is likely to be located, the measured  $S/N$  is the highest.

The results, presented in Fig. 5, show that the emission lines luminosity is powered either by star formation or by LINER-like mechanisms such as shocks. In particular, the central parts of the disk are those dominated by star formation, while the gas at higher galactic altitudes shows characteristics of LINER emission or intermediate between the two (see the right-hand panel of Fig. 5).

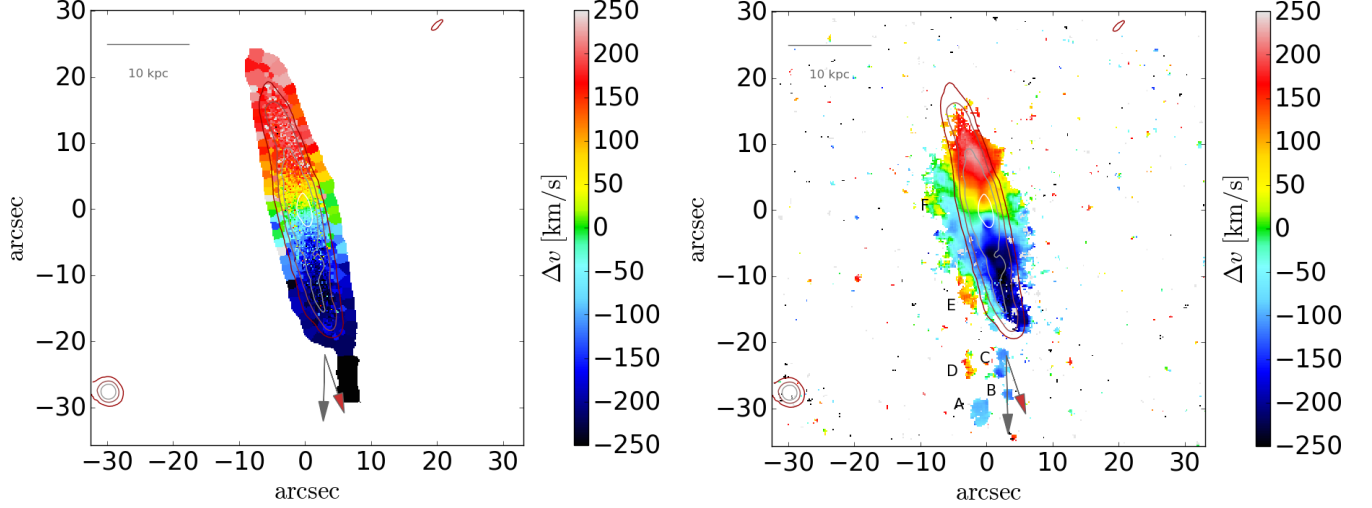
Clear signatures of stripping along the line of sight are visible as double-peaked emission lines profile, or as departure from a gaussian profile, mostly visible in  $H\alpha$ . These are located in the outskirts of the disk, in regions with a LINER emission origin.

It is interesting to notice that the regions classified as “Star Forming” in the left panel of Fig. 5, are clearly displaced towards the east with respect to the center, defined by the  $H\alpha$  continuum contour, and slightly bent with respect to the major axis.

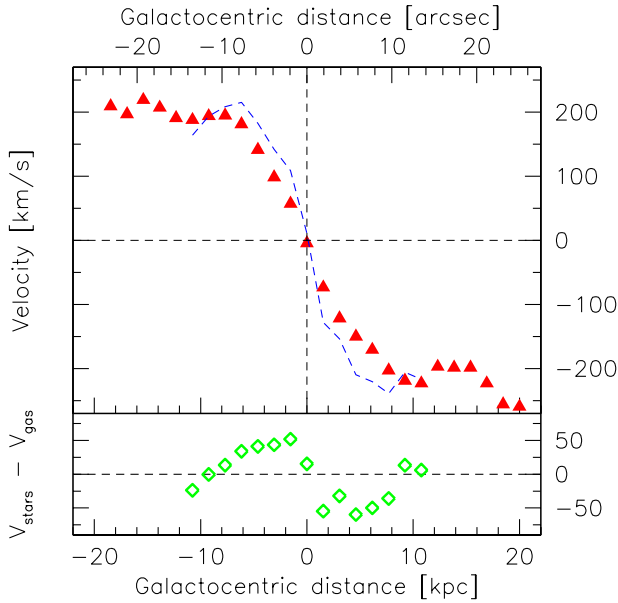
A comparison between the two panels of Fig. 3, highlights how the ionized gas disk extends to substantially shorter galactocentric radii with respect to the stellar disk, showing a clear sign of truncation.  $H\alpha$  is detected out to  $\sim 12$  kpc, while the stellar disk extends to at least  $\sim 20$  kpc. In Sect. 6 we will discuss the possible origin of this truncation.

Interestingly enough, deep Chandra archive images have detected the presence of a luminous though highly





**Figure 3.** Left panel: Stellar velocity map. Right panel: gas velocity map. The solid lines in both figures are H $\alpha$  continuum surface brightness contours in four logarithmically spaced levels. Regions labelled with letters from “A” to “F” are described in the text. The grey and red arrows point toward the BCG and the cluster X-ray emission, respectively. A cut of 4 in S/N was applied in the gas velocity map. North is up, east is left.



**Figure 4.** On the top panel, the stellar (red triangles) and gas (blue, dashed line) radial velocity profiles are displayed. On the lower panel, the difference between gas and stellar velocity.

absorbed X-ray source strongly incompatible with a possible nuclear starburst, as described in Sect. 4.4 (and Nicastro et al. in prep.). This would imply that, if an AGN is indeed the source of this luminosity, it should be highly obscured so that it would be non-detected by optical lines diagnostics.

#### 4.3. Properties of the stellar populations

We now study both the global and spatially resolved stellar populations of this galaxy by analysing the SFR as a function of time in four age bins. These are logarith-

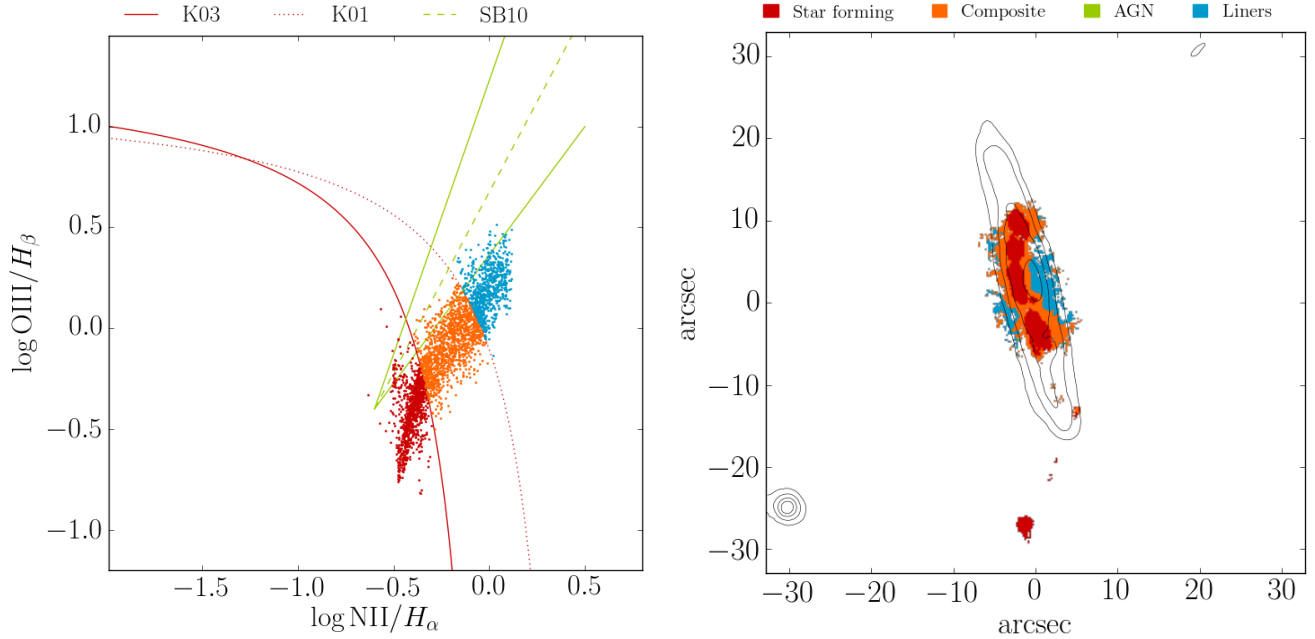
**Table 2.** Ages of the the stellar populations, in years, for which we calculate physical properties from the spectral fitting.

Bin	Lower age	Upper age
1	0	$2 \times 10^7$
2	$2 \times 10^7$	$5.72 \times 10^8$
3	$5.72 \times 10^8$	$5.75 \times 10^9$
4	$5.75 \times 10^9$	$14 \times 10^9$

mically spaced and chosen in such a way that the differences between the spectral characteristics of the stellar populations are maximal, and are defined according to Table 2.

The choice of the number of age bins and their definition is based on simulations we have performed in Fritz et al. (2007) for integrated spectra of the WINGS survey. While, on the one hand, the quality of the spectra, especially in terms of S/N, is much better for MUSE data, on the other side these spectra are sampling the rest-frame spectral region between  $\sim 4700$  and  $\sim 9000$  Å, hence missing some of those features which are normally used to constrain the stellar population properties. This is why we have decided not to push our interpretation to a higher age resolution, despite the excellent quality of our data. However, we are still satisfied by the modelling and the provided results, since it is extremely difficult to disentangle the presence of old (i.e. in the 5-14 Gyr range) stellar populations by means of non-resolved spectroscopy. Well-known effects such as the age-metallicity degeneracy, plus dust extinction, conspire to make the spectra of simple stellar populations very similar in this age range.

The total stellar mass, calculated as the sum of stel-

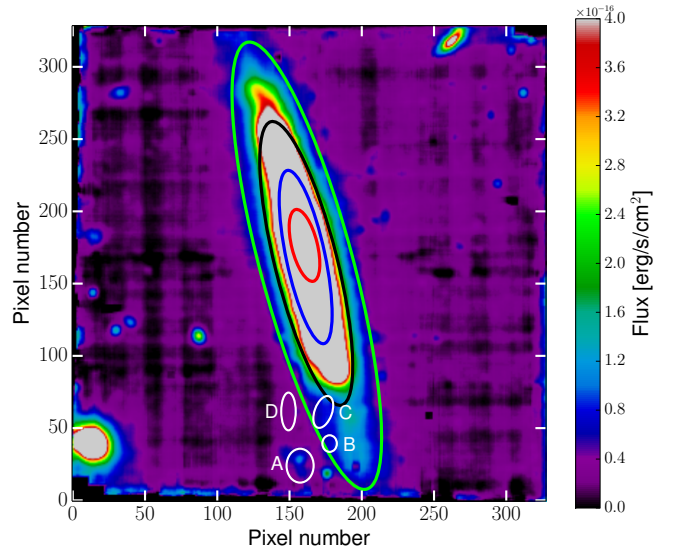


**Figure 5.** Left. Diagnostic diagram of the ionising sources across the galaxy. The red dotted and continuous lines are defined as in Kewley et al. (2001) and Kauffmann et al. (2003), respectively. The green lines are taken from (Sharp & Bland-Hawthorn 2010) (see text for details.) Right. Spatial locations of the spaxels color-coded based on the ionising source diagnostic.  $H\alpha$  continuum surface brightness contours are shown as a reference for the stellar emission.

lar masses in all the spaxels encompassed by region 4 (the larger ellipse in Fig. 6, see also Table. 3), is of  $\sim 6.5 \times 10^{10} M_{\odot}$ , and is compatible, within the uncertainties, with the value of  $4.8 \times 10^{10} M_{\odot}$  calculated from the aperture-corrected spectrum taken as part of the WINGS project. Using SINOPSIS to derive the stellar mass from the integrated spectrum of region 4, yields a value of  $5.9 \times 10^{10} M_{\odot}$ , very close to the value calculated by summing the stellar mass over all the spaxels.

Similarly to the stellar mass, the total SFR can be obtained by summing its values in each spaxel. These values, for which dust absorption has already been taken into account, mainly depend on the intensity of the  $H\alpha$  line, meaning that the possible presence of an obscured star formation component, which would only be detectable at infrared wavelengths (see Sect. 5), cannot be taken into account. The total SFR calculated in this way, is  $5.8 M_{\odot}/\text{yr}$ , about 90% of which is concentrated within the innermost parts, where dust extinction also reaches the highest values as shown in Fig. 12 (this corresponds to the spaxels enclosed within ellipse n.2 in Fig. 6).

To find possible trends in the stellar properties as a function of the position, we have considered 4 annuli, defined as the regions in between elliptical apertures, which are roughly defined to match the surface brightness intensity of the stellar emission at different levels. These are depicted in Fig. 6. Table 3 reports the physical sizes of the ellipses. Furthermore, we separately analyze the star formation histories of both the stellar tail and



**Figure 6.** The MUSE datacube integrated with respect to the wavelength. The ellipses are the areas where the SFR is computed, with the same color-coding as in Fig. 7. The white ellipses and circles on the south part are the 4  $H\alpha$  blobs as identified in Sect. 4.1.

the four  $H\alpha$  emission blobs identified in Fig. 3.

Calculating the SFR in the previously defined annuli, is an effective way to look for broad spatial trends in the average ages of the stellar populations as a function of the galactocentric distance. After the first star formation episode, when about 65% of the stellar mass was created, the galaxy underwent a decrease in the star forming activity, followed by a subsequent star forma-

Region	a	b
1	4.1	1.4
2	9.8	2.2
3	16.2	3.5
4	25.6	5.1

**Table 3.** Size, in kpc, of the major (a) and minor (b) semi-axes of the ellipses defining the regions in Fig. 6

tion episode with an intensity, relative to the previous age bin, higher in the outskirts with respect to the center.

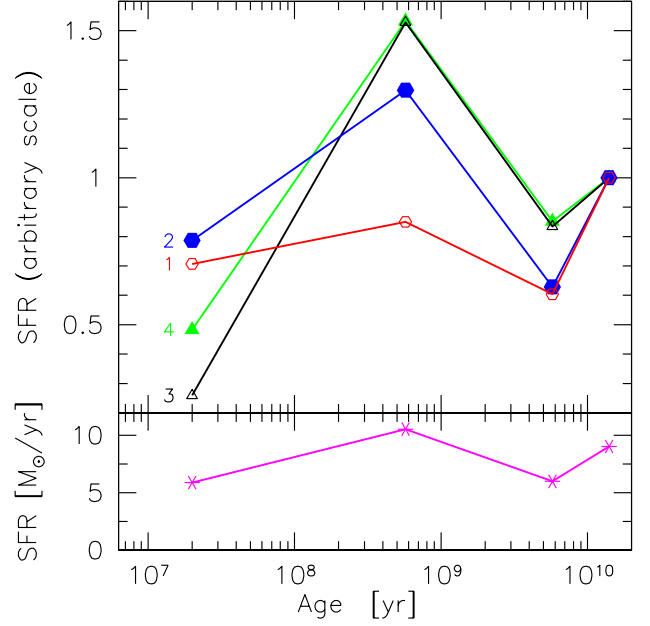
This can be seen in Fig. 7, where we show the normalised SFR a function of age and position. This is indicative of an inside-out formation scenario in the early epochs of the galaxy: the SFR decreased after the initial burst more abruptly in the innermost regions, while being sustained at a higher rate in the disk outskirts. An intense star formation activity involving the whole galaxy occurred between 20 Myr and 0.5 Gyr ago, with a much higher intensity in the outer part than in the galaxy center. During this event, the SFR increased by only  $\sim 15\%$  in the innermost region, while the outer parts experienced a boost by almost 50%.

This event converted, according to our modelling, about  $10^{10} M_{\odot}$  of gas into stars in the outer disk (i.e. the annulus between ellipses 2 and 4), an amount that represents about 15% of the currently observed total stellar mass in the whole galaxy.

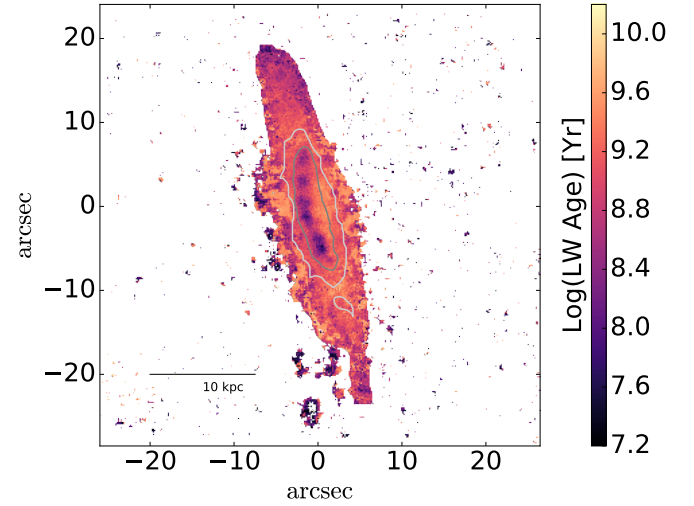
Fig. 9 presents the spatially resolved star formation rate surface density in 4 age bins. There are no signs of ongoing star formation outside the disk, except for the southern blobs where we clearly detect ionized gas. Indeed, the top-left panel in Fig. 9, shows that the most intense star forming spaxels are found within the central parts of the disk with values up to  $\sim 5 \times 10^{-2} M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-1}$ , while outside this region, very well defined by the  $H\alpha$  continuum contours, only very faint and sparse signatures of current star formation are found.

The outermost parts of the disk are dominated by intermediate-age (i.e. between  $\sim 2 \times 10^7$  and  $\sim 6 \times 10^8$  years) stellar populations; these very same stars are also the main population found in the tail departing from the southern disk that was identified in Fig. 3, where no emission lines were detected. The oldest stars are dominating the bulge of the galaxy, and they are the most concentrated population as depicted in the lower-right panel of Fig. 9.

The luminosity weighted age map, shown in Fig. 8, highlights the changes in the average age of the stellar populations at each location in the galaxy. This displays a minimum in the central parts of the galaxy, as expected given that it is at this location where the bulk of the star formation is happening. Very young ages are



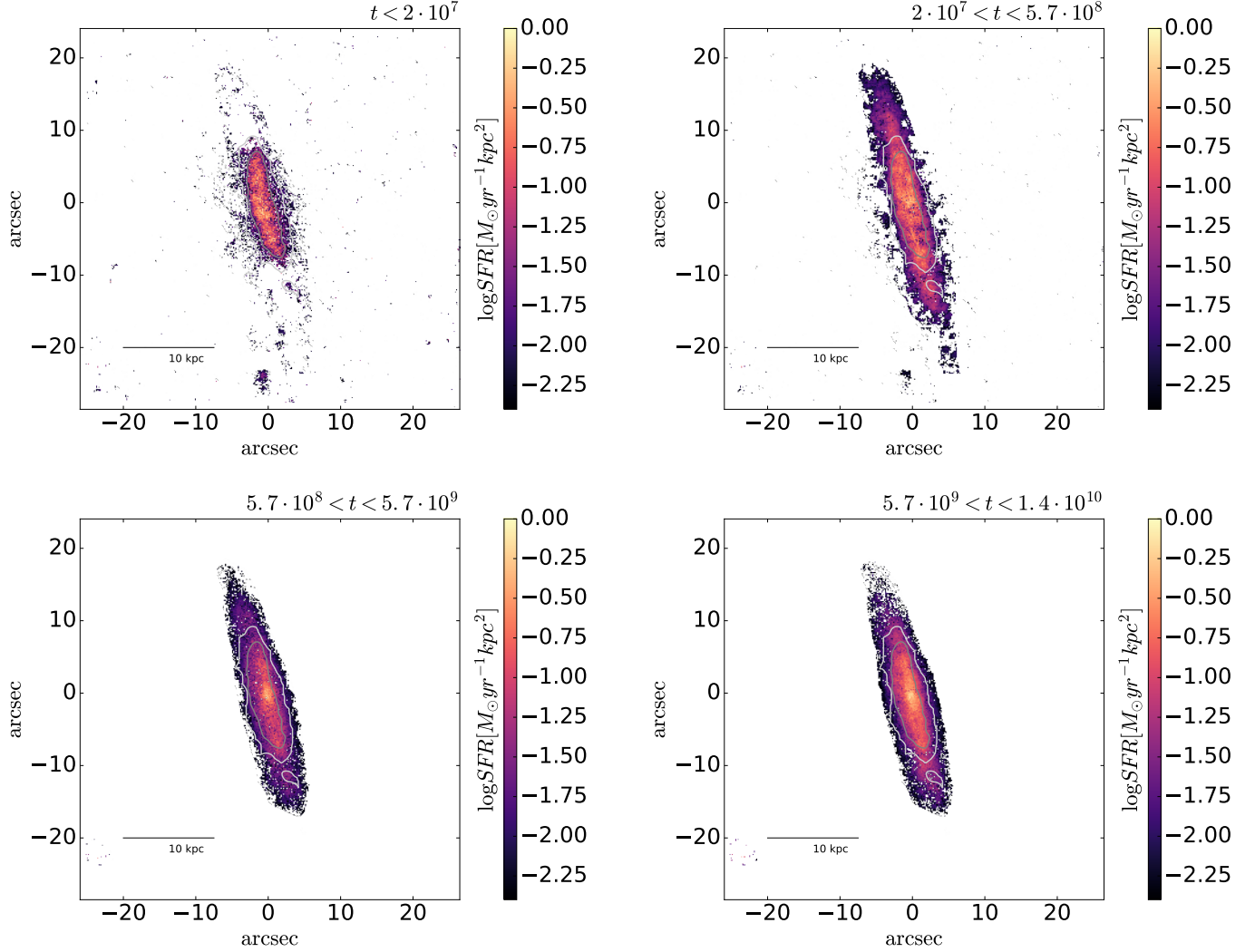
**Figure 7.** Top panel. The star formation history of the galaxy, normalised to the SFR in the oldest age bin, in the four annuli defined in Fig. 6 (the color-coding is the same) and Table 3. These are labelled from 1 to 4 going from the innermost to the outermost. Lower panel. Total SFR in the galaxy as a function of age.



**Figure 8.** Map of the luminosity-weighted stellar age as calculated from spectral modelling.

found in the blobs located in the southern outskirts as well, which are all found to be star-forming.

The map of the luminosity-weighted age (Fig. 8) shows that the four blobs defined in Fig. 3 and 6 have very young ages, consistent with observed  $H\alpha$  in emission, and a very faint stellar continuum. In the most luminous one, blob “A”,  $H\alpha$  equivalent width reaches a value of  $-64 \text{ \AA}$ . The star formation rates derived from



**Figure 9.** Star formation rate surface density as a function of position for different epochs corresponding to the 4 main SSP age bins. The contours are defined in the same manner as for Fig. 3.

SINOPSIS from the integrated spectra of the blobs, range from  $3 \times 10^{-3}$  (blob B) to  $1.2 \times 10^{-2} M_{\odot}/\text{yr}$  (blob A), while the stellar masses have values in the range between  $5.1 \times 10^6$  (blob D) and  $1.7 \times 10^8 M_{\odot}$  (blob A). Relatively young ( $\lesssim 500$  Myr) stars are present throughout all the disk.

We point out that the spatial trends we observe in the stellar population properties are very likely weakened by projection effects, given the high inclination angle of the galaxy, and might be actually even stronger.

#### 4.4. The Chandra View of the Nuclear Region of JO36

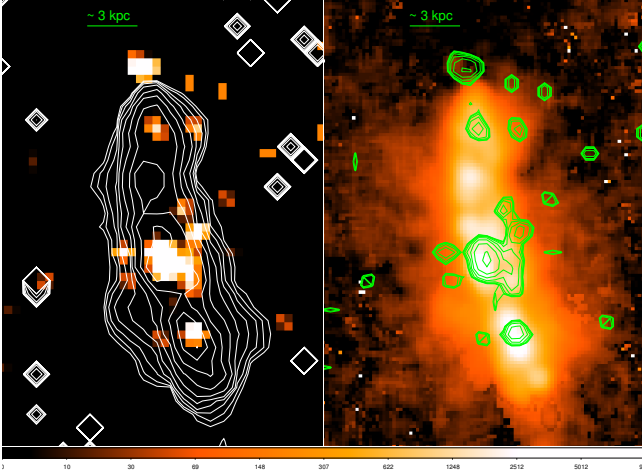
JO36 was serendipitously observed by *Chandra* on October 18th, 2002, as part of the targeted observation of the cluster Abell 160, and for a total of 58.5 ks. The galaxy is located 5.8 arcmin off-axis, with respect to the *Chandra* ACIS-I aimpoint, where the 2 keV off-axis/on-axis effective area ratio (i.e. vignetting) is  $\sim 0.9$ , and

the Point Spread Function (PSF) Encircled Energy Radius is  $\sim 1.5 - 2$  arcsec (cf. with  $\sim 0.5$  arcsec on-axis; “The *Chandra* Proposal Observatory Guide”, v. 19.0, <http://cxc.harvard.edu/proposer/POG/html/chap6.html>).

A bright X-ray nucleus is clearly detected (Fig. 10, left panel), at a position coincident with that of the bright  $H\alpha$  nucleus (Fig. 10, right panel), together with several fainter point-like X-ray sources (most likely Ultra-Luminous X-ray - ULX - sources; Nicastro et al., in preparation), aligned with the galaxy’s edge-on disk seen in  $H\alpha$  (white contours superimposed to the X-ray image in the left panel of Fig. 10). Interestingly, the brightest of these off-nuclear X-ray sources is located just at the north edge of the truncated stellar disk, where little or no  $H\alpha$  emission is seen.

To estimate the X-ray luminosity of the nucleus, we extracted source and background X-ray counts respec-



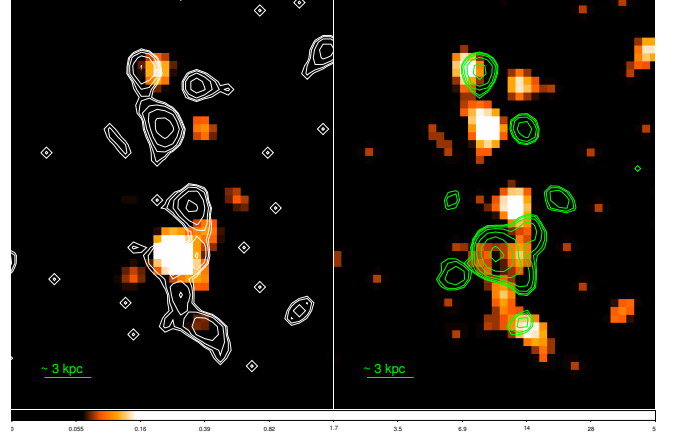


**Figure 10.** *Chandra* 0.3-10 keV (left panel) and MUSE  $H\alpha$  (right panel) images of the GASP cluster galaxy JO36: X-ray (green) and  $H\alpha$  (white) contours are superimposed on the  $H\alpha$  and X-ray images, respectively.

tively from a 3 arcsec radius circular region centred on the source centroid (RA=18.24788, DEC=15.59122) and from 4 additional 3 arcsec radius source-free circular regions located  $\sim 15$  arcsec north-east and south-east of the nucleus. The nuclear region contains 32 full band *Chandra* counts, while the 4 background regions contain a total of 7 counts. Rescaling by the 4-times source to background smaller extraction area, this gives a net number of 0.3–10 keV source counts of  $30.8 \pm 5.6$ , or a count rate of  $(5.3 \pm 1.0) \times 10^{-4}$  cts  $s^{-1}$ .

The nuclear X-ray counts are all detected above 2 keV (compare left and right panels of Fig. 11), which suggests that the X-ray emission is highly absorbed. Indeed, binning the  $\sim 31$  source net counts into bins with  $\geq 10$  counts, leaves a three-bin spectrum ( $E_{bin} = 1.8, 4.2$  and  $6.7$  keV) peaked at 4.2 keV. Modeling the spectrum with a simple power-law ( $F = A(E/E_0)^\Gamma$ ) yields an extremely flat photon spectral index  $\Gamma = -0.9$ , which also underestimates the spectrum peak count rate. Including a column  $N_H$  of intrinsic nuclear cold gas surrounding the X-ray source and attenuating the soft X-rays along our line of sight, and freezing the photon spectral index to the commonly observed AGN value of  $\Gamma = 2$  (e.g. Piconcelli et al. 2005), yields instead flat residuals and a best-fitting  $N_H = 1.1^{+0.7}_{-0.4} \times 10^{23}$   $cm^{-2}$ , as typically observed in highly obscured type 2 Seyfert galaxies (e.g. Risaliti, Maiolino, & Salvati 1999).

From the best-fitting spectral model we derive an observed (i.e. absorbed) 2–10 keV flux  $F_{2-10} = (3.5 \pm 1.5) \times 10^{-14}$  erg  $s^{-1}$   $cm^{-2}$ , which translates (at the distance of JO36) into an observed luminosity  $L_{2-10} = (1.4 \pm 0.6) \times 10^{41}$  erg  $s^{-1}$  and an intrinsic (i.e. unabsorbed) luminosity of  $L_{2-10}^{unabs} = (2.8 \pm 1.1) \times 10^{41}$  erg  $s^{-1}$ . By factoring a bolometric correction factor of  $\simeq 10$  (appropriate for  $L_{2-10} \simeq 3 \times 10^{41}$  erg  $s^{-1}$ , i.e. Marconi



**Figure 11.** *Chandra* 2-10 keV (left) and 0.3-2 keV (right) images of the GASP cluster galaxy JO36.

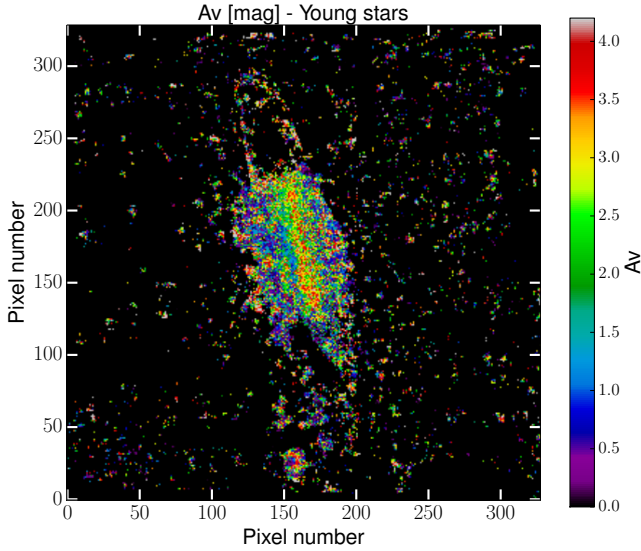
et al. 2004), we get:  $L_{Bol} \simeq 4 \times 10^{42}$  erg  $s^{-1}$ , consistent with the low luminosity end of Seyfert galaxies and thus pointing towards the presence of a buried AGN in the nucleus of JO36, which was non detected by optical diagnostic diagrams.

An additional independent (but indirect) check of the presence of an AGN in the nucleus of JO36 can be done by comparing the star formation rate density (SFRD) derived in the nuclear region through the  $H\alpha$  diagnostics ( $SFRD_{H\alpha} \simeq 0.14$   $M_\odot$   $yr^{-1}$   $kpc^{-2}$ ), with the estimate derived by assuming that all the 31 nuclear *Chandra* counts be uniformly distributed over a compact,  $\lesssim 2.7$  kpc (i.e. 3 arcsec) radius, nuclear star-bursting region and be due to a large (i.e.  $\gtrsim 100$ ) number of unresolved luminous X-ray binaries. This gives an observed 2–10 keV luminosity density of  $\mathcal{L}_{2-10} \gtrsim 7.6 \times 10^{39}$  ergs  $s^{-1}$   $kpc^{-2}$ , which translates into  $SFRD \gtrsim 1.5$   $M_\odot$   $yr^{-1}$   $kpc^{-2}$  (e.g. Ranalli, Comastri, & Setti 2003). This is more than 15 times larger than observed in  $H\alpha$ , again suggesting the presence of an AGN in the nucleus of JO36.

## 5. THE INTERSTELLAR MEDIUM IN JO36

SINOPSIS provides values for the emission lines dust attenuation, whose map we show in Fig. 12. A comparison with the same quantity calculated from the observed Balmer decrement ( $H\alpha/H\beta$ ) shows excellent agreement. Values of  $A_V$  as high as 4 are found towards the central parts of the galaxy, this being partly due to the high inclination of the galaxy disk with respect to the line of sight. This map only gives a proxy for the presence of dust, as it does not take into account the 3D structure of the galaxy, projection effects, and the fact that the most dusty regions can be completely invisible at optical wavelengths.

Deriving the amount of dust from attenuation maps in the optical is doable, but prone to the aforementioned uncertainties and is best done by means of radiative transfer models (see e.g. Popescu & Tuffs 2002; Baes



**Figure 12.** Extinction map as derived by spectral fitting.

et al. 2010; De Geyter et al. 2014; Saftly et al. 2015, and references therein), which are anyway well beyond the goals of this work.

A much more reliable way, as opposed to the extinction map, is to look at the dust thermal emission, showing up at far infrared and sub-millimetre wavelengths.

JO36 is located within a field recently observed with the infrared space observatory *Herschel* (Pilbratt et al. 2010) as part of the program KPOT\_mjuvela\_1 (P.I. Mika Juvela, Juvela 2007). These observations, taken with both the PACS (Poglitsch et al. 2010) and SPIRE (Griffith et al. 2010) instruments, reveal an intense infrared emission detected at all wavelengths (100, 160, 250, 350, and 500  $\mu\text{m}$ ).

We have reduced both PACS and SPIRE data in two steps, with the first one making use of the latest version of hipec (v14.2.0) to get the data to Level1, while the map making, de-glitching and baseline removal were performed with the latest version of the IDL package SCANAMORPHOS (v25, Roussel 2013). We have measured fluxes in apertures encompassing the whole galaxy in all maps, performing background subtraction as customary for such kind of data (see, e.g. Ciesla et al. 2012; Verstaappen et al. 2013; Cortese et al. 2014).

The much lower spatial resolution of *Herschel* data (the highest resolution is reached for PACS at 100  $\mu\text{m}$ , and is about 6''), when compared to optical images, makes it impossible to establish a spatial connection between the geometrical distribution of the dust and that of the ionized gas, as derived from MUSE data. Nevertheless, we can calculate global estimates of the total dust mass and use this value to infer the gas mass.

Dust mass can be derived by means of SED fitting using a modified black body model emission. In Ta-

ble 4 we report the measured infrared fluxes used for the modeling.

**Table 4.** Fluxes densities and corresponding uncertainties, in Jy, measured on the five *Herschel* bands from archival images.

$\lambda$ [ $\mu\text{m}$ ]	Flux	Error
100	0.77	0.05
160	1.01	0.08
250	0.47	0.04
350	0.20	0.02
500	0.07	0.01

Fig.13 shows the infrared (IR) datapoints and the fit by means of a standard modified black body model, whose parameters are the mass of dust (i.e. the normalisation), the dust temperature and the dust emissivity. The latter is parametrised through the emissivity index,  $\beta$ , as defined in the following:

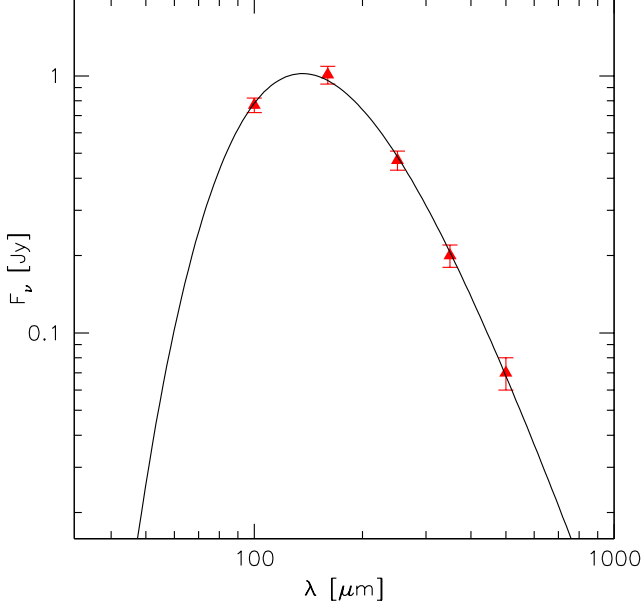
$$F_\nu = M_D k_{\nu_0} \left( \frac{\nu}{\nu_0} \right)^\beta \frac{B_\nu(T)}{D^2}, \quad (3)$$

where  $M_D$  is the dust mass,  $k_{\nu_0}$  is the dust emissivity coefficient at a reference frequency  $\nu_0$ ,  $D$  is the distance to the galaxy, and  $B_\nu$  is the Planck function (see e.g. Smith et al. 2010, for an application of this method to local galaxies). While simplistic, this fitting approach has been widely used in the literature, and has proven to give a fair physical approximation to the dust emission characteristics (Bianchi 2013).

As for the dust emissivity coefficient, we adopted the standard one from Draine (2003), which has a value of 0.192  $\text{m}^2 \text{kg}^{-1}$  at 350  $\mu\text{m}$ . The dust mass derived in this way ranges from  $\sim 6 \times 10^7$  to  $\sim 10^8 M_\odot$ . More specifically, if we leave the emissivity index  $\beta$  as a free parameter, we find a best fit for a dust temperature of  $21.42 \pm 1.80$  K, an emissivity index  $\beta = 2.17 \pm 0.32$ , and a dust mass of  $9.8^{+2.2}_{-1.8} \times 10^7 M_\odot$ . Integrating the black body model SED over the 10 to 1000  $\mu\text{m}$  range, we get an IR luminosity of  $2.59 \times 10^{10} L_\odot$ . We convert this into a SFR using the Kennicutt (1998) relation, rescaled to the Chabrier (2003) IMF by using the conversion factor as in Hayward et al. (2014):

$$SFR_{IR} = 3.0 \times 10^{-37} L_{IR} M_\odot \text{yr}^{-1} \quad (4)$$

where  $L_{IR}$  is expressed in W (note that the aforementioned conversion factor is actually calculated for a Kroupa 2001 IMF which has anyway a minimal difference with respect to IMF we adopt here, see e.g. Madau & Dickinson 2014). The SFR calculated in this way is  $2.98 M_\odot \text{yr}^{-1}$ , and it is defined as the average SFR through a timescale of  $10^8$  yr, while the one we have derived from the spectral fitting is based on the emission

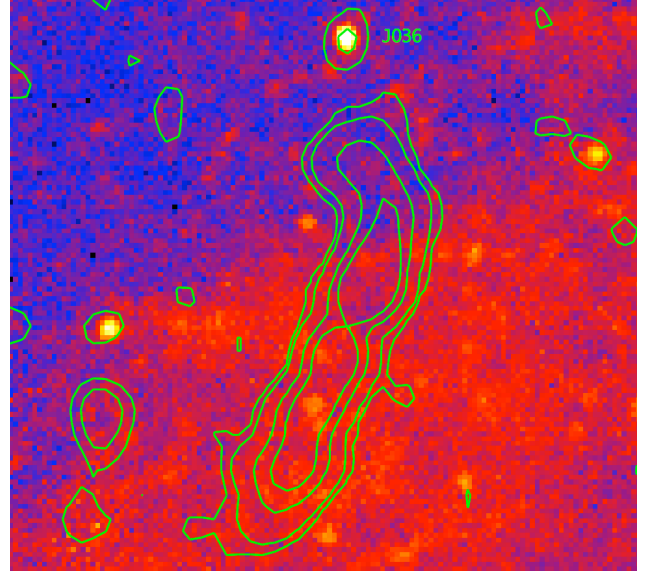


**Figure 13.** Modified black body fit (black line) to the observed *Herschel* datapoints (red triangles). A dust temperature of 20.63 K, a  $\beta = 2.15$ , and a dust mass of  $9.8 \times 10^7 M_\odot$  are derived from this model.

lines intensity, and has a much shorter timescale ( $\sim 10^7$  yr). Furthermore, the former is more strictly related to the fraction of obscured star formation, so the two values are not directly comparable. It should be also noted that, in systems with a relatively low SFR such as JO36, part of the dust luminosity might be powered by old stellar populations (see, e.g. Bendo et al. 2012; Smith et al. 2012; Viaene et al. 2014). In this case, this value should be taken as an upper limit to the amount of completely obscured star formation.

Using a lower value for  $\beta$  (1.5), the dust mass we obtain is slightly lower,  $5.8 \times 10^7 M_\odot$  (and has a higher temperature compared to the previously found value, namely  $T = 26.72$  K), but the  $160 \mu\text{m}$  point is underestimated by more than 20%, well beyond the flux uncertainty in this band.

Following Eales et al. (2012), and using their equation 2, we can derive the total gas mass (i.e. the mass of the gas in all phases) from sub-mm fluxes. Using the  $500 \mu\text{m}$  flux, and assuming the Galactic gas-to-dust ratio, we get a value of  $3.2 \times 10^9 M_\odot$ . Similarly, following a much direct and straightforward approach, we can simply convert the dust mass into a gas mass of about  $10^{10} M_\odot$  assuming the same Galactic gas-to-dust ratio of 100. Both values of the gas mass are quite consistent to those expected, within the observed dispersion, in normal, non star-bursting galaxies of similar stellar mass as JO36 (see e.g. Magdis et al. 2012; Morokuma-Matsui & Baba 2015), and might give an indication that the



**Figure 14.** SPIRE  $250 \mu\text{m}$  emission and radio contours (continuum emission at 1.4 GHz from Condon et al. 1998) of the region of the sky surrounding JO36.

majority of the gas is still retained by the galaxy.

This, of course, heavily relies on the assumption of a given gas-to-dust ratio that, for a galaxy in a cluster environment, might not be strictly true. Cortese et al. (2010), studying the spatially-resolved dust emission versus the gas content on a sample of galaxies in the Virgo cluster, found evidences of dust truncated disks in highly HI-deficient galaxies ( $def_{HI} > 0.87$ ). The fact that we observe such a high value of the dust mass, can be hence taken as an indication that the amount of atomic gas that has been stripped must yield a deficiency value smaller than 0.87. Using the definition of HI deficiency given by Chung et al. (2009), and assuming the aforementioned value for  $def_{HI}$ , we can calculate a lower limit for the HI mass in JO36. The value we derive in this way is  $\sim 1.4 \times 10^9 M_\odot$ . Again, this value compares very well to the HI mass expected for galaxies with similar stellar masses (see e.g. Popping, Somerville, & Trager 2014; Jaskot et al. 2015).

To determine the mass of the ionized gas, we have used the relation between  $H\alpha$  luminosity and the mass of ionized hydrogen, as described in Poggianti et al. (2017). This also depends on the electron density, which we have calculated from the ratio of the sulfur forbidden doublet at 6714 and 6731 Å. To calculate it we have adopted the prescription given in Proxauf, Öttl, & Kimeswenger (2014):

$$n_e = 0.0543 \cdot \tan(-3.0553 \times R + 2.8506) + 6.98 - 10.6905 \times R + 9.9186 \times R^2 - 3.5442 \times R^3 \quad (5)$$

where  $R = F_{6714}/F_{6731}$  is the ratio between the fluxes of the two lines (Poggianti et al. 2017). Eqn. 5 is valid

in the range  $0.436 \leq R \leq 1.435$ . We have used line fluxes measured by KUBEVIZ and, when  $R$  assumed a value outside the two limits, we have adopted a value equal to the closer limit. In case neither of the two lines were measurable, we took  $R = 0.966$ , which is the average between the upper and lower limit. As for the  $H\alpha$  flux, we have used the value measured by KUBEVIZ on the absorption-corrected spectra. The effect of dust attenuation was also corrected for, with the value  $A_V$  that SINOPSIS provides for the young (i.e. lines-emitting) stellar populations. This has the advantage that an extinction value is given also when  $H\beta$  is not available because too faint. No extinction correction was applied in case  $A_V$  was not calculated for a given spaxel. The total ionized gas mass computed in this way amounts to  $6.9 \times 10^8 M_\odot$ . This mass is  $2\sigma$  lower than the value expected for galaxies of similar stellar mass (Popping, Somerville, & Trager 2014).

JO36 is also detected by the NVSS radio survey (Condon et al. 1998), and has a (broad band) flux density of  $4.3 \pm 0.5$  mJy at 1.4 GHz. The emission in this band is dominated by the radio continuum and it is therefore another tracer of the ionized gas. In Fig. 14 we present infrared data together with the radio (1.4 GHz) contours superimposed. The long radio tail is likely related to the nearby BCG (VV 382 or GIN 049), and there is a clear detection at the position of JO36.

These data can be used to derive another, independent estimate of the ionized gas mass. Using the prescription given in Galván-Madrid et al. (2008), which assumes that the gas is homogeneously distributed within a sphere, we find a value which is two orders of magnitude higher with respect to the previously calculated one, meaning that assumptions made regarding the geometrical distribution of gas are probably too strong, and this method cannot be applied to a jellyfish like JO36 to derive the ionized gas mass. Emission from supernovae at these frequencies might also bias the result.

A further estimate of the SFR can be given using this data, with the advantage that this tracer is insensitive to dust extinction. With a luminosity  $L_{1.4} = 1.67 \times 10^{22}$  W·Hz<sup>-1</sup>, and using the prescription from Hopkins et al. (2003) (see their Equations 1 and 2), we find a SFR of 9.2  $M_\odot$ /yr, which is significantly higher than the value we have derived from MUSE data analysis. This might be an indication of the presence of a substantial completely dust obscured star formation, which would reveal itself in the mid-infrared, or of the possible contamination of radio AGN emission.

To summarise, we have derived total gas masses from IR and sub-mm data in the range between  $3.2 \times 10^9$  and  $10^{10} M_\odot$ . Both estimates rely on the assumption that a Galactic gas-to-dust ratio can be used for this galaxy. A lower limit of  $1.4 \times 10^9 M_\odot$  to the HI mass was

extrapolated from the substantial presence of dust that we used as an indicator of the maximum degree of HI deficiency. All of these values agree with the gas mass expectations in galaxies of similar stellar mass. The exception to this is the ionized gas mass, which is lower by more than  $2\sigma$  when compared to the average relation for similar galaxies.

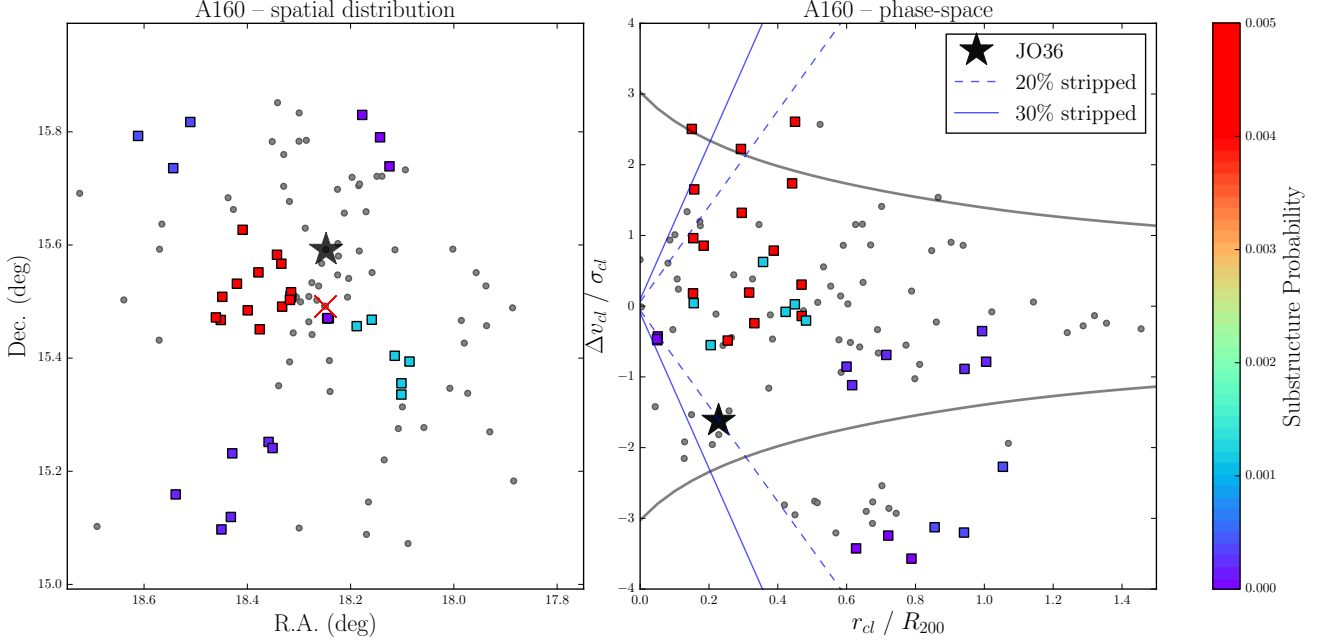
The SFR calculated from the spectral fitting is 5.8  $M_\odot$ /yr. As this naturally takes into account the effect of dust extinction, the value of 3  $M_\odot$ /yr calculated from IR luminosity is partly accounted for in the former SFR indicator. An extinction independent value for the SFR is given by the radio continuum, which provides a value of 9.2  $M_\odot$ /yr, significantly higher with respect to the aforementioned values. This can be due to either the presence of heavily obscured star formation, which would show up mostly at mid infrared wavelengths, or to the possible contamination by the AGN (see Sect. 4.4).

## 6. DISCUSSION

The most important results we obtained so far can be summarized as follows.

- the stellar disk extends out to a radius of about 20 kpc, while the ionized gas only reaches galactrocentric distances of about 12 kpc. We interpret this as a clear evidence of a truncated ionized gas disk;
- a stellar tail, extending by  $\sim 5$  kpc with respect to the main body of the disk, is observed towards the south;
- four  $H\alpha$  blobs are present southwards of the galaxy, close to the aforementioned tail;
- the (ionized) gas velocity field is noticeably distorted, especially when compared to the stellar one;
- the dust mass is compatible with that expected in “normal” field galaxies having similar stellar masses. This strongly suggests that dust has not been stripped. If dust is used as a tracer for the presence of gas, we infer a total gas mass in the range expected for the physical characteristics of this galaxy. The fact that no evidence is found of a significant dust stripping constraints the HI deficiency level of the galaxy, and was used to estimate a lower limit of the HI mass;
- the mass of ionized gas is at the lower limit with respect to the value expected for galaxies of similar stellar mass;
- star formation is currently happening only in the central region of the galaxy, within a 10 kpc radius,





**Figure 15.** Left: The position in the sky of JO36 spectroscopic members from OmegaWINGS (small black points), JO36 (star), and the BCG (red cross). Squares correspond to identified substructures, which have been color-coded according to their probability to be random fluctuations (i.e. values close to zero indicate highly significant substructure detections, Biviano et al. in preparation). Right: Phase-space diagram with symbols as in the left panel. Curves show the escape velocity in a Navarro, Frenk, & White (1997) halo. The dashed and solid blue lines correspond to 20 and 30% of total gas mass stripped in JO36 by the ICM in a Virgo-like cluster (see text for details).

while the external ( $r > 10$  kpc) parts of the disk are dominated by stars with ages  $< 500$  Myr;

- the star formation history of the galaxy shows evidences of an inside–out formation process. An enhancement in the SFR happened between 20 and 500 Myr ago, more deeply affecting the outer disk with respect to the central regions.

In the next Section (6.1), we present various pieces of evidences of active ram pressure on this galaxy, while in the followings we try now to build a self-consistent picture that can interpret the aforementioned observed features simultaneously.

### 6.1. The strength of ram-pressure in JO36

Given JO36’s vicinity to the core of A160, and its high velocity within the cluster (see the phase–space diagram, as in Jaffé et al. 2015, shown in Fig. 15), it is likely that ram-pressure stripping is or has been at play. The ram-pressure by the ICM can be estimated as  $P_{ram} = \rho_{ICM} \times v_{cl}^2$  (Gunn & Gott 1972), where  $\rho_{ICM}(r_{cl})$  is the radial density profile of the ICM,  $r_{cl}$  the clustercentric distance, and  $v_{cl}$  the velocity of the galaxy with respect to the cluster. Since A160 is a low mass cluster (velocity dispersion =  $561 \text{ km s}^{-1}$ ), we assume a smooth static ICM similar to that of the Virgo cluster. Utilizing the density model used by Vollmer et al. (2001), we can get

an estimate of the ram pressure at the projected  $r_{cl}$  and line-of-sight velocity of JO36:

$$P_{ram} = 9.5 \times 10^{-14} \text{ Nm}^{-2} \quad (6)$$

To assess whether this is enough to strip gas from JO36, we compute the anchoring force of the galaxy assuming an exponential disk density profile for the stars and the gas components ( $\Sigma_s$  and  $\Sigma_g$  respectively) defined as:

$$\Sigma = \left( \frac{M_d}{2\pi r_d^2} \right) e^{-r/r_d}, \quad (7)$$

where  $M_d$  is the disk mass,  $r_d$  the disk scale-length and  $r$  the radial distance from the center of the galaxy. For the stellar component of JO36 we adopted a disk mass  $M_{d,stars} = 5.2 \times 10^{10} M_\odot$  (accounting for a bulge to total ratio of 0.2), and a disk scale-length  $r_{d,stars} = 4.63$  kpc, obtained by fitting the light profile of the galaxy. For the gas component we assumed a total mass  $M_{d,gas} = 0.1 \times M_{d,stars}$ , and scale-length  $r_{d,gas} = 1.7 \times r_{d,stars}$  (Boselli & Gavazzi 2006).

The anchoring force in the disk can then be computed as:  $\Pi_{gal} = 2\pi G \Sigma_g \Sigma_s$ , at different radial distances from the centre of the galaxy ( $r$ ). We find that the condition for stripping is met at  $r \sim 13.4$  kpc, where  $\Pi_{gal}$  drops below  $P_{ram}$ . This truncation radius corresponds to  $\sim 21\%$  of the total gas mass stripped, (see reference dashed line in the right panel of Fig. 15).

The estimated fraction of stripped gas is consistent with the lower limit of HI mass derived in Section 5 (from the dust content), that when compared to the gas mass in our disk model, yields an upper limit for the fraction of stripped gas  $\sim 27\%$ . It is also interesting to compare the expected stripping from our modeling with the observed truncation radius. Taking the extent of H $\alpha$  emission as a good estimate, we get an observed truncation radius of  $r_t = 11$  kpc, which corresponds to more stripping than predicted ( $\sim 27\%$  of the total gas mass; solid blue line in Fig. 15). We note however that the predicted stripping suffers from uncertainties in the galaxy and cluster model, and that it does not take into account possible inhomogeneities of the ICM.

To test for the presence of substructures within the cluster, we selected galaxies with significant deviations from the cluster velocity dispersion (coloured symbols) and found that JO36 does not belong to any clear group. A dynamical analysis of A160 (Biviano et al. in preparation) reveals several substructures, shown with coloured squares in Fig. 15. However, there is no evidence for JO36 to reside in any of these substructures. On the contrary, its phase-space position suggests that this galaxy has fallen recently into the cluster as an isolated galaxy.

An additional possibility to explain the small difference between the predicted (dashed line) and measured stripping (solid line) is that this galaxy is not on its first infall, but instead it has already passed its peak stripping point (at the location of the solid blue line in phase-space) and is now gaining distance from the cluster centre.

Overall, our analysis shows that JO36 must have lost between  $\sim 20$  and  $30\%$  of its total gas mass via ram-pressure stripping by A160’s ICM.

We now propose two mutually exclusive scenarios, each of which is successful in explaining some of the observed features listed above while, at the same time, failing to account for others. The difference in the two scenarios simply lies in the direction of the tangential velocity of the galaxy.

### 6.2. *Tangential velocity towards the north (1)*

JO36 was selected as a possible jellyfish candidate because of the presence of a tail, pointing towards the location of the BCG, visible in WINGS V and B band images. This, together with the detection of few relatively bright H $\alpha$  spots located close to this tail, are features that we recover in MUSE data as well (see the left-hand panel of Fig. 3 for the tail, and the right-hand panel in the same figure for the blobs).

These features can be explained in a scenario where the galaxy has a velocity component in the opposite direction to the location of both the tail and the blobs, moving away from the cluster center (the direction to-

wards the X-ray center and the location of the BCG are indicated by the two arrows in Fig. 3). In this picture, the denser gas in the central regions of the cluster exerted a ram pressure stripping (RPS) force that would be able to rip part of the gas away from the galaxy, which would be now found in the form of the observed H $\alpha$  emitting blobs. Something very similar, although to a much more spectacular degree, is observed in other jellyfish galaxies (e.g. Merluzzi et al. 2013, 2016; Fumagalli et al. 2014; Poggianti et al. 2017; Moretti et al. 2017b), where bright tails and star forming blobs are found in locations opposite to the direction of the galaxy motion. Just like the aforementioned cases, the blobs we observe here retain the disk velocity.

### 6.3. *Tangential velocity towards the south (2)*

While scenario (1) is the most likely explanation for the star-forming blobs, there is a number of other observed features that it cannot account for.

Analyzing Fig. 3, we have already pointed out how the locus where the gas has a zero radial velocity component is twisted in an irregular “U” shape, with a concavity directed towards the north, and it reaches galactocentric radii of about 8 kpc towards the same direction. Similarly, gas with positive radial velocities is found on the same side (the region labelled as “F” in Fig. 3). This twisting of the gas rotational axis is a feature that is predicted as a consequence of RPS by the aforementioned simulations of Merluzzi et al. (2016), where the direction of the bending is directly related to the velocity of the galaxy on the plane of the sky which, in the case of JO36, would be pointing to the cluster center.

This scenario would also explain why the star forming region, clearly visible in the right-hand panel of Fig. 5, is slightly bent in a “C” shape pointing towards the south-east and offset, with respect to the stellar continuum, in that direction. If shocks with the intracluster gas are responsible for the enhanced star formation, it is hence logical to expect that this would happen first in the direction of the interaction between the two gas components which, in this scenario, would be on this side of the disk.

### 6.4. *More than just one mechanism at play?*

JO36 shows clear signature of past and ongoing RPS. This is further confirmed by the phase-space diagram (Fig. 15) that shows that the galaxy is well within the region where ram pressure is strong enough to eventually strip all the gas.

Hence, while it is quite clear that we are observing RPS signatures, scenario (2) cannot naturally explain the presence of the four gas blobs for which we would need to appeal to other phenomena. On the other hand, scenario (1) seems to be partially in contradiction with

the gas velocity map. Such a distortion naturally arises due to RPS if the galaxy would be moving in the opposite direction, i.e. towards the cluster center.

Furthermore, the stellar tail, visible in Fig. 3, does not fit either of the two proposed scenarios, and needs other physical mechanisms to be invoked. While being a morphological feature clearly departing from the disk, it does not seem to have any counterpart with similar characteristics in the north side of the galaxy. Moreover, the (stellar) velocities follow the trend observed in the disk itself, as expected if this was a natural prosecution of the disk, and have the highest values found in the galaxy.

If this tail was the result of gas stripping from the outer disk by ram pressure, one would expect it retains a similar velocity with respect to the region within the disk where it came from. The measured velocities are higher by up to 50 km/s than to the rest of the disk (see also the rotation curve in Fig. 4).

In addition, the average age of the stellar populations of this tail is compatible with a formation epoch up to 500 Myr ago, hence significantly older with respect to the ages derived for the blobs that are rich in ionized gas and still actively star forming. If this was to happen in a stripped gas component, we should not be observing it still being attached to the galaxy, as the gas would have had the time to move away and detach from the galaxy's disk. On the other side, stars are not affected by RPS.

For these reasons, we can conclude that RPS cannot be the mechanism by which this stellar tail originated, and we would need to invoke a different mechanism to explain its formation.

According to numerical simulations performed by Kronberger et al. (2008a), aimed at studying the effect of ram pressure on the star formation of spiral galaxies, an observed enhanced star formation rate in stellar populations with ages in the 20–500 Myr range, is a direct effect of the interaction between the gas in the galaxy and that in the intracluster medium. This would somehow date the beginning of the interaction between the galaxy and the hot gas in the cluster.

Following the same authors, when the interaction is “edge-on”, such as in our case, the gas loss is much lower compared to a face-on interaction, the main signature of ram pressure being a distortion and compression in the gas disk, which is indeed what we observe. Enhanced SFRs by up to a factor of 3 are observed in these simulations, compatible with the values we have derived by spectral fitting (see also Koopmann & Kenney 2004).

Numerical simulations from the same group (Kronberger et al. 2008b), focussing on the effects on the rotation curves and velocity fields of the gas, show a stronger distortion of the gas distribution in edge-on in-

teractions, as compared to the face-on case. They also observe a displacement on the rotation axis of stars and gas, something that we instead do not find.

Integrating the observed datacube with respect to the wavelength coordinate, we get a high S/N picture which better allows to view the morphology of the lowest surface brightness components of the galaxy (Fig 6). By doing this, we can confirm the absence of a tidal feature in the northern disk, while 2 of the H $\alpha$  blobs appear to be almost embedded within the disk, making it unclear whether they effectively are jellyfish morphological features or nothing more but regions of residual star formation from a quenched disk. Nevertheless, the brightest and largest blobs (A and D) are, even in projection, too far away to fill in this picture.

Relying on IR or sub-mm data to calculate the total gas mass, we find that possible gas stripping has to be limited to a small amount of material. Different methods to infer the gas mass yield values in fairly good agreement with respect to each other, and these point to a regular gas-to-stellar mass content.

In any case, given the relatively low mass of the A160 cluster ( $L_X = 10^{43.6}$  erg/s, Ebeling et al. 1996, and  $\sigma_{gal} = 561$  km/s, Moretti et al. 2017a), and given the dependency of the RPS effect on the cluster gas density, we do not expect, at least as long as short time scales are concerned, massive gas losses, most of all given the geometry of the galaxy motion (numerical simulations by Kronberger et al. 2008a, have shown that edge-on systems are much less prone to gas loss) and the mass of the galaxy.

One possible explanation for the extended stellar disk (i.e. the tail), is that it could be the result of a localized interaction. Kronberger et al. (2006) performed numerical simulations to study how galaxy encounters influence the kinematics of stellar disks. For given sets of simulations parameters, they find that a fly-bys can affect the stellar rotation in the disk outskirts in different ways depending on the configuration of the encounter and on the line-of-sight of the observation. Some of the rotation curves they extract from their simulations resemble the asymmetry we observe in JO36 stellar kinematic, and in particular in the tail. Similarly, Pedrosa et al. (2008) claim that bifurcations, i.e. asymmetries in the outer parts of a rotation curve as we observe in JO36, are a clear indicator of a recent galaxy encounter.

It would be tempting to identify in one of the blobs (e.g. blob A, the most massive one) the possible candidate for this kind of interaction. In this case, we would be witnessing the later phases of an encounter between JO36 and a dwarf galaxy. Nevertheless, the metallicity values we derive for blob A are way too high to be compatible with those of a dwarf system, and it is fully consistent with the metallicity of the outer gas remained

for now in the disk.

## 7. SUMMARY AND CONCLUSIONS

In this work, we have undertaken an analysis of the properties of the stellar populations and of the interstellar medium in JO36, a galaxy in the Abel 160 cluster, with slightly distorted optical morphology, possibly a signature of gas stripping. We have used these observations to validate our spectral fitting code, SINOPSIS, for applications to IFU data analysis by comparing its results with those obtained from GANDALF, a well known and widely used code generally exploited to derive the properties of the emission lines and of the underlying stellar populations. This comparison indicates that our approach gives robust results fully compatible with those obtained with GANDALF on the same dataset.

From the results of the kinematic analysis and of the stellar populations properties in this galaxy, we draw the following conclusions:

1. JO36 shows no spectacular morphological signatures of gas stripping such as those commonly encountered in the so-called jellyfish galaxies, but the ionized gas disk is clearly truncated with respect to the stellar one;
2. if any gas stripping has occurred in the past, it most likely involved a minor fraction of the total gas in the galaxy. A substantial gas depletion due to an intense star forming episode happened about 500 Myr ago, could have been concurred to the creation of the truncated ionized gas disk;
3. from a kinematical point of view, the rotation curve of the gas displays asymmetries in the outer parts of the disk, with a rotation axis strongly distorted and suggestive of a velocity component towards the center of the cluster. This is in agreement with numerical simulations of RPS acting with a relative velocity parallel to the galaxy plane (edge-on);
4. the presence of H $\alpha$  blobs close to the southern edge of the galaxy, might suggest a tangential velocity component in the north direction, something that seems to be incompatible with the morphological characteristics of the gas rotational axis;
5. the presence of a stellar tail in the southern disk, with no clear counterpart in the opposite direction, cannot be attributed to ram pressure effects. Its velocities follow the stellar rotation curve from the inner parts, and are higher than those measured across the whole galaxy disk. Composed by stellar populations of ages between  $2 \times 10^7$  and  $5 \times 10^8$  yr, and showing no evidences for the presence of gas, it

can be the result of a gravitational interaction with a less massive galaxy, as suggested by numerical simulations;

6. there is no evidence of AGN activity, at least as far as diagnostic lines are concerned. However, the detection of a strong emission in the X-rays, seems to indicate the possible presence of a deeply obscured AGN (Nicastro et al. in prep.).

JO36 is a moderately massive spiral which is subject to RPS as several pieces of evidence suggest. The truncated ionized gas disk, the low ratio of HII/M $_{\star}$  with respect to similar galaxies, the disturbed gas kinematic, the presence of ionized gas regions clearly detached from disk, its location on the phase-space diagram, and finally an episode of enhanced star formation strongly involving the outer disk, all point to ram pressure being caught on the act.

We also speculate that the stripped gas is probably a minor fraction of the gas in the galaxy. By indirect calculations of the amount of total gas and of HI, we find that the gas content is quite typical, given the stellar mass of the galaxy. Furthermore, the moderately intense star formation likely induced by shocks with the intra-cluster gas, has consumed a substantial amount of gas. Indeed, in the analysis of their numerical simulations, [Kronberger et al. \(2008a\)](#) propose that losses of gas by RPS together with depletion due to star formation, is the reason for the decrease, and eventual quenching, of the star formation rate.

What is less clear is instead the direction of the ram pressure or, equivalently, of the galaxy motion. In fact, we could not reconcile in a self consistent picture the presence of ionized gas in the southern part of the galaxy, indicating a velocity component towards the north, with the distorted shape of the gas rotational axis, suggesting instead a velocity component towards the south. Dedicated numerical simulations are probably the best tool to figure out the kinematic of the galaxy and give hints on its orbit, to better understand the relation between its star formation history and the interaction with the cluster environment.

With respect to the first point in our final remarks, it should be noted that MUSE data for this galaxy basically cover all of its disk but we cannot draw any conclusion on the possible presence of stripped tails at larger distances, which passed unobserved in optical images. Furthermore, we lack HI data to derive the atomic mass distribution, and give a final word about the dynamical history of the galaxy.

Both [Poggianti et al. \(2016\)](#) and [McPartland et al. \(2016\)](#) stress the importance of spectroscopic data to unveil the occurrence of gas stripping signatures, as opposed to pure photometric detections. In this particular



case, MUSE data turned out to be critical to uncover a second dynamical mechanism affecting this galaxy, most likely a gravitational interaction with a much less massive galaxy.

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